Cover page

Title: *Life Limiting Rationale for a Level D HUMS Utilized for Maintenance Credits*

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ABSTRACT

A rotorcraft Health and Usage Monitoring System (HUMS) has two important roles. First, by accounting for maneuvers and conditions that are more severe than those that the aircraft was designed for, premature fatigue and other types of catastrophic failure can be avoided. Second, by obtaining credit for in-service time that is less demanding than those for which the aircraft was certified. Extending the aircraft's service time can then be justified, which will allow for more economical operations [1]. However, while usage monitoring has prevented failures, to date, no applicants have successfully followed the guidance of the Federal Aviation Administration (FAA) Advisory Circular (AC) 29 Miscellaneous Guidance (MG) 15 [2] to develop individual aircraft usage credits.

It is conceivable that parts, for which maintenance credits may be applied, are critical components with potentially catastrophic results upon failure. Thus, there must be a very high assurance that the component does not fail. It is the purpose of this document to show that critical parts may be monitored in an end-to-end HUMS with individual component assurances that are lower than Level A. This is an important concern, as FAA guidance does not allow for Level A HUMS certification.

A significant difference between the HUMS application and normal critical avionics functions is the time to failure. Most critical avionic applications are analyzed with a standard Functional Hazard Assessment (FHA). In this type of analysis, the failure is as likely to occur in hour one as it is to occur in later times. In the end-to-end HUMS system, the failure of a part is probable on at the end of its life. As this is different than previous applications a statistical theory was developed to handle the overall assurance of not exceeding a maximum life limit.

The results show that not all of the statistics are currently available for large life extension. As would be expected with small data sets, there is little certainty in the estimated parameters. Populating a statistical database may not allow for initial life extension, but will allow for future life extension as the HUMS statistics converge.

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INTRODUCTION

A rotorcraft Health and Usage Monitoring System (HUMS) has two important roles. First, by accounting for maneuvers and conditions that are more severe than those that the aircraft was designed for, premature fatigue and other types of catastrophic failure can be avoided. Second, by obtaining credit for in-service time that is less demanding than those for which the aircraft was certified. Extending the aircraft's service time can then be justified, which will allow for more economical operations [1]. However, while usage monitoring has prevented failures, to date, no applicants have successfully followed the guidance of the Federal Aviation Administration (FAA) Advisory Circular (AC) 29 Miscellaneous Guidance (MG) 15 [2] to develop individual aircraft usage credits. This document identifies provides the rationale for using a single thread Level D HUMS for obtaining maintenance credits as developed by the Embry-Riddle Aeronautical University (ERAU) HUMS team [3].

A major concern in the use of a HUMS for maintenance credits is the individual element assurance levels within the end-to-end HUMS from a top-level perspective. It is conceivable that parts, for which maintenance credits may be applied, are critical components with potentially catastrophic results upon failure. Thus, there must be a very high assurance that the component does not fail. It is the purpose of this document to show that critical parts may be monitored in an end-to-end HUMS with individual component assurances that are lower than Level A. This is an important concern, as FAA guidance does not allow for Level A HUMS certification. This approach takes into consideration the fact that the end-to-end system includes multiple use of the airborne equipment collecting the flight data, transfer of the collected data to the ground station, and processing of the aggregated data. In addition, it is highly desirable to use Commercial off the Shelf (COTS) hardware and software in the end-to-end system, which typically cannot be approved above Level D [4].

The rationale in this document shows that a single thread HUMS with Level D components can monitor a critical part with the appropriate of confidence of not exceeding the life limits. A significant difference between the HUMS application and normal critical avionics functions is the time to failure. Most critical avionic applications are analyzed with a standard Functional Hazard Assessment (FHA). In this type of analysis, the failure is as likely to occur in hour one as it is to occur in later times. In the end-to-end HUMS system, the failure of a part is probable on at the end of its life. As this is different than previous applications a statistical theory was developed to handle the overall assurance of not exceeding a maximum life limit.

The results show that not all of the statistics are currently available for large life extension. It does, however, quantify what statistics must be monitored to make large extensions possible in the future. As would be expected with small data sets, there is little certainty in the estimated parameters and, therefore, the initial life limits will remain close to their pre-HUMS values. As data is collected, the variance and biases will converge and maximum life extension will be possible without compromising safety.

LIFE LIMITING RATIONALE

A primary application of HUMS is Usage Monitoring (UM) for extension of the service time of life-limited parts. Life limited parts may include parts that are considered catastrophic in the event of failure [5]. It is impracticable and inconsistent with current FAA guidance to certify the HUMS itself to Level A assurance even though it may be monitoring a Level A component. The inclusion of COTS hardware in the end-to-end HUMS limits the certification to Level D [3]. It is important to show that a Level D assurance can be used to monitor higher-level aircraft criticality. Table I lists the variables used in the derivation of the safety level for a general end-to-end HUMS.

TABLE I. LIST OF VARIABLES

Variable	**Description**
N_{margin}	Reduction in the number of counting cycles to ensure that the N_{max} is not exceeded
N_{max}	Maximum number of cycles permitted
$N_{MaxHUMS}$	Maximum number of allowable cycle counts by the HUMS equipment with α confidence that the actual count has not exceeded N_{max}
$\left.\widehat{N}\right\|_{\max HUMS}$	Estimation of $N_{MaxHUMS}$ cycle counts
$\widehat{N}$	Estimated number of cycles
N_{HUMS}	Actual number of counts accumulated by the HUMS
μ_M	Percent loss of counts per count due to process M
μ_L	Percent loss of counts per flight hour due to process L
T	Total time on the component
$\widehat{N}_{Hr}$	Estimated number of counts per hour for the component
CI	Interval of counts that has α confidence in containing the number of lost counts
s	Overall HUMS end-to-end system deviation in loss hours/hour
t_α	The value of the Student's t distribution for the appropriate confidence values of α
α	This subscript is the confidence value corresponding to the upper tail area of a normal distribution, for example 95% confidence α=0.05
υ	Degrees of freedom of the system
N_{hr}	Estimated number of HUMS per hour for the component

It is assumed that the parameter being monitored has a maximum value, N_{max}. This is the maximum count or number of cycles that the manufacture specifies as the life of the part. It will be shown here that high confidence in not exceeding N_{max} can be obtained by quantifying the HUMS performance and adjusting the maximum number of HUMS counts, N_{HUMS}, accordingly. In doing this, the number of HUMS counts is reduced from the maximum number of counts by a factor that accounts for missing data and variation in the data.

$$N_{M\arg in} = N_{Max} - N_{MaxHUMS} \tag{1}$$

The magnitude of count margin, N_{margin}, is dependent upon the HUMS performance and data rates. Higher assurance levels and data rates results in a smaller count margin. HUMS equipment that tends to miss counts will have a larger number of lost counts. To maintain the system criticality, it is not necessary for the HUMS to have extremely high assurance in the counts. It is, however, very important that the system errors and variation be well quantified. There are two drivers that determine the desired HUMS performance: 1) Cost of lost component life due to a high N_{loss} and 2) The increased cost of the HUMS system with decreasing N_{loss}.

$$N_{Loss} = N_{Max} - \widehat{N}\Big|_{MaxHUMS} \tag{2}$$

The number of lost counts can be quantified if all of the HUMS components can be quantified. The two key factors in determining the overall system performance are the determination of overall system count deviation and loss. If these can be specified end-to-end the number of lost counts can be determined.

$$\widehat{N} = N_{HUMS} + \widehat{N}\sum_{1}^{M}\mu_M + T\widehat{N}_{Hr}\sum_{1}^{L}\mu_L \tag{3}$$

An estimate of the actual number of counts can be determined from the number of HUMS counts and the loss per flight hour in percent. Large losses can be attributed to the HUMS sample rate. Other losses can be attributed to HUMS failures and inaccuracies. Data loss due to sample rate is typically the largest source of missing counts. This occurs in a digital system when the exceedence is between data samples and the duration is less than the sample time. For nominal HUMS this may be as high as 10-15% of the counts [6].

Thus from an understanding of the losses in counts in the HUMS, an estimate of the actual number of counts, $\widehat{N}$, at any time can be determined from the HUMS count, N_{HUMS}. There is, of course, uncertainty associated with this estimate of the actual number, N. The actual number of counts, N, is assumed to now have a zero-mean normal probability distribution about the count estimate, $\widehat{N}$.

Standard Deviation in Component Counts

The end-to-end system standard deviation can then be used to determine a knock down value of counts that provides a given confidence limit on the actual number of counts, N, from the estimate $\widehat{N}$.

There is a possibility that the HUMS has either an over count or an under count about the estimate, $\widehat{N}$. The critical case for the overall system is under counts. The maximum HUMS count, $N_{maxHUMS}$, must be reduced by the number of possible undercounts. These undercounts are quantified via probability; thus it is prudent to ensure that there is a given confidence that the number of lost counts is not underestimated.

The interval of confidence from the estimated number of counts, $\widehat{N}$, is specified in the following way:

$$CI = \frac{st_{\alpha}T\widehat{N}_{Hr}}{\sqrt{\upsilon}} \tag{4}$$

In this case, the Student's t values should be used for the appropriate value of the degrees of freedom [7]. Thus, immature data sets will yield large confidence intervals and large losses in potential life extension. Once mature data sets have been determined, the values for an infinite degree of freedom should be obtainable. Table II shows the values of the Student's t function at an infinite degree of freedom and one degree of freedom.

Estimating Component Counts

The total loss of counts will be the addition of the known losses plus a knockdown value to ensure, with a particular confidence that the actual value of N remains in the confidence interval. The required margin is the known losses of counts plus a factor to ensure that statistically N remains under N_{max} in regardless of variation in the data, equation 5. The maximum number of counts that the device can count before retirement is the counts allowed minus the margin, equation 6.

$$N_{M\arg in} = \sum_{1}^{M} \mu_M N_{HUMS} + TN_{Hr}\sum_{1}^{L}\mu_L + \frac{st_{\alpha}TN_{Hr}}{\sqrt{\upsilon}} \tag{5}$$

$$N_{MaxHUMS} = N_{Max} - N_{M\arg in} \tag{6}$$

TABLE II. CRITICICAL VALUES OF STUDENT'S T

Critical Values of Student's t		
Confidence	t_{α} (ν=∞)	t_{α} (ν=1)
95%	1.645	6.314
99%	2.326	31.821

Substituting Equation 1 into Equation 5 yields an equation for the maximum number of HUMS counts at any time. Many of these variables vary over short periods of time. A good statistical database is required to forcast a good estimate of the maximum number of HUMS counts.

$$N_{MaxHUMS} = N_{Max} - \left[\widehat{N}\sum_{1}^{M}\mu_M + TN_{Hr}\sum_{1}^{L}\mu_L TN_{Hr} + TN_{Hr}\frac{st_\alpha}{\sqrt{\upsilon}} \right] \tag{7}$$

As the component ages, many of the required statistics needed to predict the maximum number of HUMS counts may converge. If these statistics converge than at the maximum number of HUMS counts, the number of HUMS counts and the maximum number of HUMS counts are the same. Thus the following can be stated:

$$\lim_{N_{HUMS} \to N_{MaxHUMS}} N_{HUMS} = N_{MaxHUMS} \tag{8}$$

In addition, as time progresses towards the life limit of the part, the number of cycles per hour should become stable and trend towards a constant. Similar to the HUMS count, the product of the average number of counts per hour and the total time on the component should approach the maximum number of HUMS counts.

$$\lim_{N_{HUMS} \to N_{MaxHUMS}} t_{TT}\widehat{N}_{Hr} = \widehat{N} \tag{9}$$

Thus, from Equation 9, Equation 7 at $N_{maxHUMS}$ becomes:

$$N_{MaxHUMSx} = N_{Max} - \left[\widehat{N}\sum_{1}^{M}\mu_M + \widehat{N}\left(\sum_{1}^{L}\mu_L + \frac{st_\alpha}{\sqrt{\upsilon}} \right) \right] \tag{10}$$

At this point, it is necessary to determine a value for the estimated number of counts at $N_{maxHUMS}$. Evaluating Equation 3 at $N_{maxHUMS}$ and applying it to Equation 7 becomes:

$$\widehat{N} = N_{MaxHUMS} + \widehat{N}\sum_{1}^{M}\mu_M + \widehat{N}\sum_{1}^{L}\mu_L \tag{11}$$

Solving for the estimated number of counts at $N_{maxHUMS}$ yields:

$$\widehat{N} = \frac{N_{MaxHUMS}}{1 - \sum_{1}^{M}\mu_M - \sum_{1}^{L}\mu_L} = \frac{N_{MaxHUMS}}{a} \tag{12}$$

Where:

$$a = 1 - \sum_{1}^{M} \mu_M - \sum_{1}^{L} \mu_L \tag{13}$$

Then, substituting Equation 11 into Equation 9:

$$N_{MaxHUMSx} = N_{Max} - \left[\frac{N_{MaxHUMS}}{a} \sum_{1}^{M} \mu_M + \frac{N_{MaxHUMS}}{a} \left(\sum_{1}^{L} \mu_L + \frac{st_\alpha}{\sqrt{\upsilon}} \right) \right] \tag{14}$$

Isolating $N_{maxHUMSx}$:

$$N_{Max} = N_{MaxHUMSx} + \left[\frac{N_{MaxHUMS}}{a} \sum_{1}^{M} \mu_M + \frac{N_{MaxHUMS}}{a} \left(\sum_{1}^{L} \mu_L + \frac{st_\alpha}{\sqrt{\upsilon}} \right) \right] \tag{15}$$

$$N_{Max} = \frac{N_{MaxHUMSx}}{a} \left(a + \sum_{1}^{M} \mu_M + \sum_{1}^{L} \mu_L + \frac{st_\alpha}{\sqrt{\upsilon}} \right) \tag{16}$$

Solving for $N_{maxHUMSx}$:

$$N_{MaxHUMSx} = \frac{N_{Max} a}{a + \sum_{1}^{M} \mu_M + \sum_{1}^{L} \mu_L + \frac{st_\alpha}{\sqrt{\upsilon}}} \tag{17}$$

Substituting back in for a:

$$N_{MaxHUMSx} = \frac{N_{Max} \left(1 - \sum_{1}^{M} \mu_M - \sum_{1}^{L} \mu_L \right)}{1 - \sum_{1}^{M} \mu_M - \sum_{1}^{L} \mu_L + \sum_{1}^{M} \mu_M + \sum_{1}^{L} \mu_L + \frac{st_\alpha}{\sqrt{\upsilon}}} \tag{18}$$

Simplifying:

$$N_{MaxHUMSx} = \frac{N_{Max} \left(1 - \sum_{1}^{M} \mu_M - \sum_{1}^{L} \mu_L \right)}{1 + \frac{st_\alpha}{\sqrt{\upsilon}}} \tag{19}$$

And, finally, rearranging:

$$N_{MaxHUMSx} = \frac{N_{Max}}{1 + \frac{st_\alpha}{\sqrt{\upsilon}}} \left(1 - \sum_{1}^{M} \mu_M - \sum_{1}^{L} \mu_L \right) \tag{20}$$

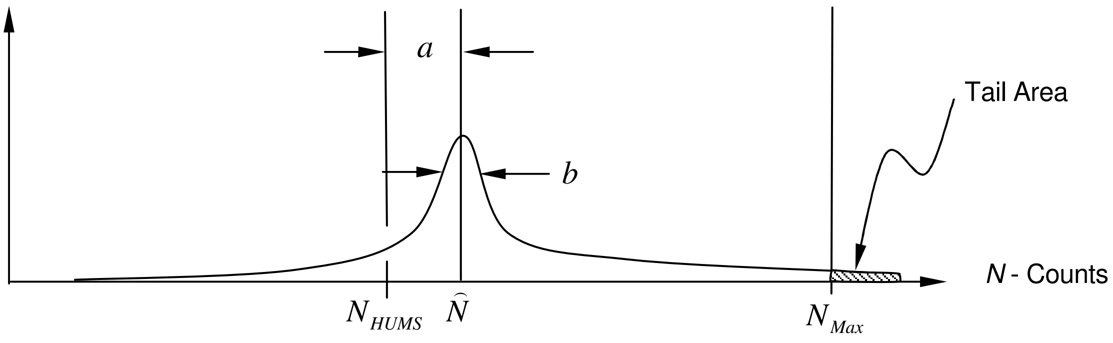

Figure 1. Graphical Depiction of N_{HUMS} Statistics

Figure 1 is a graphical depiction of the top level statistics for ensuring N_{HUMS} does not exceed N_{max}. Where:

$$a = \sum_{1}^{M} \mu_M N_{HUMS} + \sum_{1}^{L} \mu_L T N_{Hr} \tag{21}$$

$$b = s \tag{22}$$

As seen from the derivation and Figure 1, the required level of assurance can be achieved for maintenance credits even if the part is a critical part. This differs from the normal FHA in that the likelihood of an occurrence is not the same in the first hour versus later hours. Rather, the probability of failure increases with increasing part life.

HUMS Count of Component Retirement

At the retirement of the part, two important statistics have been determined for this particular application: 1) the number of counts per hour on average for the HUMS and 2) an estimate of the actual number of counts per flight hour.

$$N_{Hr} = \frac{N_{HUMS}}{t_{TT}} \tag{23}$$

$$\widehat{N}_{Hr} = \frac{\widehat{N}}{t_{TT}} \tag{24}$$

The following is an example problem to illustrate the sensitivity of the system to particular variables. The constants chosen here are representative of a typical system with one exception. All of the deviation in the system is dues to the HUMS and is specified at $1\text{x}10^{-5}$, which corresponds to Level D assurance. Table III lists the values required for the example problem.

Example Problem	
N_{Max}	50,000
μ_M	0.10
μ_L	0.01
s	$1x10^{-5}$
t_α	2.326

TABLE III. REQUIRED VALUES FOR EXAMPLE PROBLEM

$N_{maxHUMS}$ is 45,044 counts for this case. The estimate of the number of the number of actual counts is 49,998 and there are only two counts lost due to Level D assurance. Thus, the system is relatively insensitive to the assurance level of the HUMS.

CONCLUSIONS

This document shows that it is possible to implement a Level D HUMS with limited redundancy to obtain usage credits for critical helicopter components. The end-to-end system must, however, use statistical databases and historical data to determine new life limits. Immature databases will yield little or no extension. Maximum life extension with equivalent levels of safety will be realized as the multi-component database grows.

A fundamental explanation for the use of a single thread Level D HUMS is an order of magnitude analysis. It is known that there will be data losses as high as 10^{-1}, losses due to the HUMS at 10^{-5} (Level D) or 10^{-9} (Level B) are, therefore, not significant in a non-real time end-to-end system. Initial HUMS will have to quantify these losses. A major source of data loss is digital conversion, quantization. Thus, initial systems may require parallel analog systems to statistically quantify these losses for various flight regimes and helicopter usages.

From an end-to-end perspective, there are sufficient mitigation processes that can be put into place to ensure equivalent levels of safety for usage credits. The efficiency and ability to reach maximum life extension, however, is dependant upon an accurate database and may not be obtainable from the production HUMS hardware. Thus, the initial prototype HUMS designed for the ERAU research project should be capable of steady state data collection (production HUMS) and collection of all data needed to populate the initial database (additional analog system).

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